Large mass dilepton production from jet-dilepton conversion in the quark-gluon plasma

Yong-Ping Fu, Yun-De Li

Department of Physics, Yunnan University, Kunming 650091, China

Abstract

We calculate the production of large mass dileptons from the passage of jets passing through the quark-gluon plasma. Using the relativistic kinetic theory, we rigorously derive the production rate for the jet-dilepton conversion in the hot medium. The jet-dilepton conversion is compared with the thermal dilepton emission and the Drell-Yan process. The contribution of the jet-dilepton conversion is not prominent for all values of the invariant mass M, and the Drell-Yan process is found to dominate over the thermal dilepton emission and the jet-dilepton conversion for $M > 2.5$ GeV at RHIC. The jet-dilepton conversion is the dominant source of large mass dileptons in the range of 4 GeV $< M <$ 10 GeV at LHC.

Keywords: Jet-dilepton conversion; Relativistic heavy ion collisions; Dilepton

1. Introduction

Finding the quark-gluon plasma (QGP) is one of the most important goal in the studies of the relativistic heavy ion collisions. The real and virtual photons are considered to be a useful probe for the investigation of the evolution of the QGP due to their very long mean free path. In the relativistic heavy ion collisions dileptons are produced from various sources. These include the dileptons from the Drell-Yan process [1], thermal dileptons from the QGP [2, 3, 4, 5] and the hadronic gas [6, 7, 8], dileptons from the jet-dilepton conversion in the hot medium [9, 10], and dileptons from the hadronic decays occurring after the freeze-out [11, 12, 13].

The measurement of the dilepton continuum at Relativistic Heavy Ion Collider (RHIC) energies was performed by the PHENIX experiments for

Au+Au collisions at $\sqrt{s_{NN}}$ =200 GeV [14, 15, 16, 17]. The dilepton yield in the low mass range between 0.2 and 0.8 GeV is enhanced by a factor of 2∼3 compared to the expectation from hadron decays. In fact, such phenomenon was also found at Super Proton Synchrotron (SPS) [18], this dilepton excess at SPS was successfully interpreted by the models of the dropping or melting mass in a hot medium due to the chiral symmetry restoration, but such modifying scenarios can not well explain the excess in the low mass region at RHIC energies [11, 19].

In the intermediate mass region between ϕ and J/Ψ resonances the dominant contribution arises from the correlated decays of charm mesons [9, 10]. This region has been suggested as a candidate to search for the thermal dilepton emission, since its contribution could be comparable to that of charm decays [15]. The intermediate mass dilepton excess observed by the NA50 and NA60 experiments has suggested that the intermediate mass dileptons are partly produced from the QGP, and not just charm decays [20, 21, 22].

In Refs. [9, 10] the authors have calculated the production of large mass dileptons originating from the passage of the jets passing through the QGP at leading order, and have suggested that the jet-dilepton conversion as a new dilepton source would confirm the occurrence of the jet-plasma interactions and the existence of the QGP. The yield of large mass dileptons may be enhanced by the new source of the dilepton production. However, the numerical treatment used by Ref. [9] is not proper [10].

In the present work, we rigorously derive the production rate for the jet-dilepton conversion by using the relativistic kinetic theory. We compare the contribution of the jet-plasma interaction with the thermal emission and the Drell-Yan process. Numerical results indicate that the contribution of the jet-dilepton conversion is not prominent at RHIC energies. The Drell-Yan process is the dominant source of large mass dileptons for $M > 2.5$ GeV at RHIC. The jet-dilepton conversion starts playing an interesting role at Large Hadron Collider (LHC) energies. The jet-plasma interactions are found to dominate over the Drell-Yan process and the thermal dilepton emission in the range of 4 GeV $< M <$10 GeV at LHC. By comparing with the yield of the Drell-Yan process, we find that the spectrum of the jet-dilepton conversion is reduced rapidly with the invariant mass at RHIC and LHC energies.

This article is organized as follows. In Sec.2 we investigate the production rate of the jet-dilepton conversion, the thermal dilepton emission and the Drell-Yan process are also presented. The numerical results and discussion are given in Sec.3. Finally, a summary is presented in Sec.4.

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2. Formulation

2.1. Thermal dileptons and jet-dilepton conversion

The quark jets crossing the hot and dense medium can produce large mass dileptons by annihilation with the thermal antiquarks ($q_{jet}\bar{q}_{th} \to l^+l^-$ and $q_{th}\bar{q}_{jet} \to l^+l^-$). By using the relativistic kinetic theory, the production rate for the above annihilation process can be written as

$$R_{jet-l^+l^-} = \int \frac{d^3p_1}{(2\pi)^3} \int \frac{d^3p_2}{(2\pi)^3} f_{jet}(\boldsymbol{p_1}) f_{th}(\boldsymbol{p_2}) \sigma(M) v_{12}. \tag{1}$$

The cross section of the $q\bar{q} \to l^+l^-$ interaction is given by

$$\sigma(M) = \frac{4\pi}{3} \frac{\alpha^2}{M^2} N_c N_s^2 \sum_q e_q^2, \tag{2}$$

where the parameters N_c and N_s are the color number and spin number, respectively. The relative velocity is

$$v_{12} = \frac{(p_1 + p_2)^2}{2E_1 E_2}. \tag{3}$$

In the relativistic collisions, $|\boldsymbol{p}| \simeq E$, the integration over $d^3p = |\boldsymbol{p}|^2 d|\boldsymbol{p}| d\Omega$ can be done with the relatively simple result

$$\frac{dR_{jet-l^+l^-}}{dM^2} = \frac{\sigma(M)M^2}{2(2\pi)^4} \int d|\boldsymbol{p_1}| \int d|\boldsymbol{p_2}| f_{jet}(\boldsymbol{p_1}) f_{th}(\boldsymbol{p_2}), \tag{4}$$

where the distribution of thermal partons is $f_{th}(\boldsymbol{p}) = \exp(-E/T)$. The limits of the $d|\boldsymbol{p_2}|$ integration are given by $[\infty, M^2/(4|\boldsymbol{p_1}|)]$ due to the definition of the invariant mass $M^2 = (p_1 + p_2)^2 = 2|\boldsymbol{p_1}||\boldsymbol{p_2}|(1 - \cos\theta_{\angle 12})$. Then we have

$$\frac{dR_{jet-l^+l^-}}{dM^2} = \frac{\sigma(M)M^2}{2(2\pi)^4} \int d|\boldsymbol{p_1}| f_{jet}(\boldsymbol{p_1}) T e^{-\frac{M^2}{4|\boldsymbol{p_1}|T}}. \tag{5}$$

If the phase-space distribution for the quark jets $f_{jet}(\boldsymbol{p})$ is replaced by the thermal distribution $f_{th}(\boldsymbol{p})$ in Eq.(5), one can obtain the rate for producing thermal dileptons as [2]

$$\frac{dR_{th}}{dM^2} = \frac{\sigma(M)M^3}{2(2\pi)^4} T K_1 \left(\frac{M}{T}\right), \tag{6}$$

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Table 1: Initial conditions of the hydrodynamical expansion [10]: initial time(τ_0), initial temperature(T_0) and critical temperature(T_c).

Energy	$\tau_0(fm/c)$	T_0(MeV)	T_c(MeV)
RHIC	0.26	370	160
LHC	0.088	845	160

where the Bessel function is $K_1(z) = \sqrt{\pi/(2z)}e^{-z}$. If the QGP is created in the relativistic heavy ion collisions, the plasma may reach kinetic equilibrium quickly [9]. In 1+1 dimension Bjorken expansion, the system temperature evolves as $T = T_0 \left(\tau_0/\tau\right)^{1/3}$ [23], where $\tau_0 \sim 1/(3T_0)$ is the initial time when the temperature reaches T_0 [24, 25, 26](see Table 1). In the Bjorken model, the transverse density of nucleus is assumed to be constant. Since a nucleus does have a transverse density profile, the initial temperature of the system can be assigned by the transverse profile function as $T(r, \tau_0) = T_0[2(1 - r^2/R_\perp^2)]^{1/4}$ [24, 25] while performing the space-time integration $d^4x = \tau d\tau r dr d\eta d\phi$. The limits of the integration over the time τ are $[\tau_0, \tau_c]$ for the QGP phase and $[\tau_c, \tau_h]$ for the mixed phase, such that

$$\int d\tau = \int_{\tau_0}^{\tau_c} d\tau + \int_{\tau_c}^{\tau_h} d\tau f_{QGP}(\tau), \tag{7}$$

where $\tau_c = \tau_0(T_0/T_c)^3$ is the critical time when the QGP phase transfers into the mixed phase, and $\tau_h = r_d\tau_c$ is the time when the mixed phase transfers into the hadronic phase. The fraction of the QGP matter is $f_{QGP}(\tau) = (r_d\tau_c/\tau - 1)/(r_d - 1)$, here $r_d = g_Q/g_H$ is the ratio of the degrees of freedom in the two phases, we have $g_Q = 42.25$ for the three flavors of quarks and $g_H = 3$ for the hadronic gas of pions [10, 26].

The phase-space distribution of the quark jets produced in the relativistic heavy ion collisions is [24, 25]

$$\begin{aligned}
f_{jet}(\boldsymbol{p}) &= \frac{(2\pi)^3}{g_q \pi R_\perp^2 \tau p_T \cosh y} \frac{dN_{jet}}{d^2p_T dy} R(r)\delta(y - \eta) \\
&\times \Theta(\tau - \tau_i)\Theta(\tau_{max} - \tau)\Theta(R_\perp - r),
\end{aligned} \tag{8}$$

where $g_q = 6$ is the spin and color degeneracy of the quarks (and antiquarks), $R_\perp = 1.2A^{1/3}fm$ is the transverse radius of the system, η is the space time rapidity, $R(r) = 2(1 - r^2/R_\perp^2)$ is the transverse profile function, $\tau_i \sim 1/p_T$ is the formation time of the quark or antiquark jet, τ_{max} is smaller than the

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lifetime of the QGP and the time taken by the jet produced at position $\boldsymbol{r}$ to reach the surface of the plasma.

Jets crossing the hot and dense plasma will lose their energy. Induced gluon bremsstrahlung, rather than elastic scattering of partons, is the dominant contribution of the jet energy loss [26, 27, 28]. Based on the AMY formulism [29], the energy loss of the final state partons can be described as a dependence of the final state parton spectrum dN_{jet}/dE on time [26]. The energy loss is scaled as the square of the distance traveled through the hot medium [30]. Jets travel only a short distance through the plasma, and do not lose a significant amount of energy. Quark jets lose energy at less than half the rate as gluon jets, and the quark jets form the main fraction of jet events [24]. The energy loss effect of jets before they convert into dileptons is found to be small, just about 20% [25].

2.2. Jets production

The cross section for producing jets in hadronic collisions ($A + B \rightarrow jets + X$) can be factored in the perturbative QCD (pQCD) theory as [31]

$$\frac{d\sigma_{jet}}{d^2p_Tdy} = \sum_{a,b} \frac{1}{\pi} \int_{x_a^{min}}^{1} dx_a G_{a/A}(x_a, Q^2) G_{b/B}(x_b, Q^2) \frac{x_a x_b}{x_a - x_1} K_{jet} \frac{d\hat{\sigma}_{ab \rightarrow cd}}{d\hat{t}}, \quad (9)$$

where $x_a(x_b)$ is the momentum fraction of the parton $a(b)$ of the nucleon $A(B)$. The momentum fractions with the rapidity y are given by

$$x_a^{min} = \frac{x_1}{1 - x_2}, \quad (10)$$

$$x_b = \frac{x_a x_2}{x_a - x_1}, \quad (11)$$

where the variables are $x_1 = x_T e^y/2$, $x_2 = x_T e^{-y}/2$, $x_T = 2p_T/\sqrt{s_{NN}}$. p_T is the transverse momentum of the final state partons, $\sqrt{s_{NN}}$ is the center of mass energy of the colliding nucleons. The parton distribution for the nucleus is given by

$$G_{a/A}(x_a, Q^2) = R_A^a(x_a, Q^2) \left[Z f_{a/p}(x_a, Q^2) + (A - Z) f_{a/n}(x_a, Q^2) \right]/A, \quad (12)$$

where $R_A^a(x_a, Q^2)$ is the nuclear modification of the structure function [32], Z is the number of protons, A is the number of nucleons. The functions
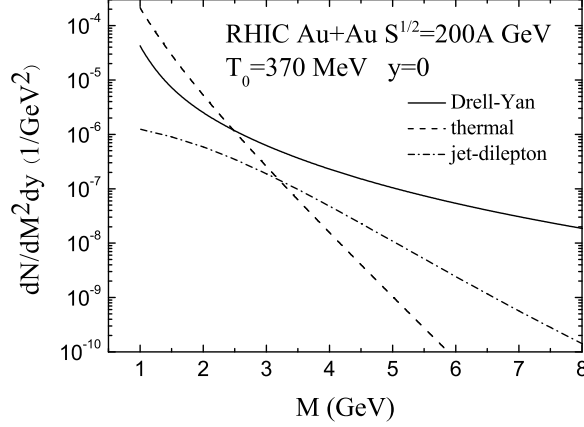
Figure 1: Dilepton yield for central Au+Au collisions at $\sqrt{s_{NN}}$ =200 GeV. We show the dileptons from the QGP (dash line), dileptons from the Drell-Yan process (solid line), and dileptons from the passage of jets passing through the hot and dense plasma (dash dot line).

$f_{a/p}(x_a, Q^2)$ and $f_{a/n}(x_a, Q^2)$ are the parton distributions of the proton and neutron, respectively [33]. We choose $Q^2 = p_T^2$. $d\hat{\sigma}_{ab\to cd}/d\hat{t}$ is the cross section of parton collisions at leading order, these processes are: $q\bar{q} \to q'\bar{q}'$, $qq' \to qq'$, $q\bar{q}' \to q\bar{q}'$, $qq \to qq$, $q\bar{q} \to q\bar{q}$, $qg \to qg$, $q\bar{q} \to gg$, $gg \to q\bar{q}$ and $gg \to gg$ [34]. One should note that the gluon jets contribute only at higher order. K_{jet} is the pQCD correction factor to take into account the next-to-leading order (NLO) effects, we use $K_{jet} = 1.7$ for RHIC and 1.6 for LHC [26].

The yield for producing jets in the relativistic heavy ion collisions is given by

$$\frac{dN_{jet}}{d^2 p_T dy} = T_{AA} \frac{d\sigma_{jet}}{d^2 p_T dy}(y = 0),\tag{13}$$

where $T_{AA} = 9A^2/(8\pi R_\perp^2)$ is the nuclear thickness for central collisions [24, 25].

2.3. Drell-Yan process

In the central collisions of two equal-mass nuclei with mass number A the yield for producing Drell-Yan pairs with the invariant mass M and rapidity
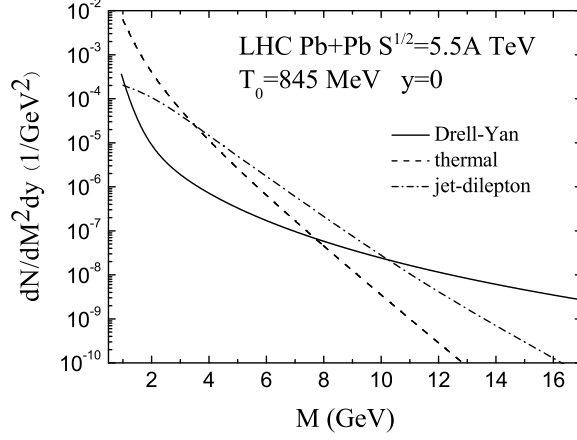
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Figure 2: Same as Fig.1 but for central Pb+Pb collisions at $\sqrt{s_{NN}}$ =5.5 TeV.

y can be obtained as [9]

$$\frac{dN_{DY}}{dM^2dy} = T_{AA}\frac{d\sigma_{DY}}{dM^2dy}(y=0) \tag{14}$$

in terms of the cross section of the Drell-Yan process in nucleon-nucleon collisions [1],

$$\frac{d\sigma_{DY}}{dM^2dy} = K\frac{4\pi\alpha^2}{9M^4}\sum_q e_q^2[x_aG_{q/A}(x_a,Q^2)x_bG_{\bar{q}/B}(x_b,Q^2)$$

$$+x_aG_{\bar{q}/A}(x_a,Q^2)x_bG_{q/B}(x_b,Q^2)], \tag{15}$$

where the momentum fractions with rapidity y are

$$x_a = \frac{M}{\sqrt{s_{NN}}}e^y, \tag{16}$$

$$x_b = \frac{M}{\sqrt{s_{NN}}}e^{-y}. \tag{17}$$

Here the nuclear effects are considered. A K factor of 1.5 is used to account for the NLO corrections [20].

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3. Numerical results and discussion

Figures 1 and 2 present our results for thermal dileptons, dileptons from the Drell-Yan process, and dileptons from the jet-dilepton conversion in the hot and dense plasma at RHIC and LHC energies, respectively. We find that the contribution of the jet-dilepton conversion is not prominent at RHIC energies. The Drell-Yan process is found to dominate over thermal dilepton emission and the jet-dilepton conversion in the region of $M >$2.5 GeV at RHIC energies(see Fig.1). The spectrum of dileptons from the passage of jets interacting with thermal partons falls off with the invariant mass M faster than the spectrum of the Drell-Yan process at RHIC. The jet-dilepton conversion starts playing an interesting role at LHC energies. The jet-dilepton conversion is the dominant source of large mass dileptons in the range of 4 GeV$< M <$10 GeV at LHC energies(see Fig.2). The spectrum of the jet-dilepton conversion drops rapidly with the M for $M >$10 GeV by comparing with the Drell-Yan process at LHC.

The higher order (NLO) pQCD corrections are accounted for by a energy and p_T dependent K factor, but in the high-energy collisions the p_T dependence of the K factor is weak, therefore the K factor is assumed to be constant [9, 25]. No K factor for the Drell-Yan process has been used in Ref.[9], and the K_{jet} factor of 2.5 used for both RHIC and LHC in Ref. [9] is larger than the K_{jet} factor used in this article.

The jets produced in initial parton collisions are defined by all partons with transverse momentum $p_T^{jet} \gg$1 GeV [9, 10]. The dilepton production is sensitive to the choice of the cutoff p_T^{jet}. In order to avoid such sensitivity, the authors of Ref. [9] have constrained a lower cutoff $p_T^{jet} \geq$4 GeV at RHIC and LHC energies. We adopt this limit in the integration of Eq.(5).

The main background for the dilepton production in the intermediate and large mass region is the decay of open charm and bottom mesons. The $c\bar{c}(b\bar{b})$ pairs are produced from the initial hard scattering of partons and can thereafter fragment into $D(B)$ and $\bar{D}(\bar{B})$ mesons. If the energy loss of heavy quarks crossing the hot medium is considered, the contribution of the decay of open charm and bottom mesons will be suppressed [35, 36]. In this article, this background is not considered, the background of J/Ψ vector meson decay is also not concerned.

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4. Summary

We have calculated the production of dileptons produced from the passage of jets interacting with thermal partons in the hot and dense plasma. We have rigorously derived the production rate of the jet-dilepton conversion by using the relativistic kinetic theory. The spectrum of the jet-dilepton conversion has been compared with the thermal dilepton emission and the Drell-Yan process. The numerical results indicate that the contribution of the jet-dilepton conversion is not prominent for all values of the invariant mass M at RHIC energies. However, this contribution becomes evident at LHC energies. The jet-dilepton conversion is the dominant source of large mass dileptons in the range of 4 GeV $< M <$ 10 GeV at LHC.

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